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Parametrization of the regular equivalences of the canonical controller

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V. CONCLUSION

We have addressed the problem of robust H_∞ control for linear NCSs. We have proposed a new Lyapunov–Krasovskii functional, which is based on both the lower and upper bounds of time-varying network-induced delay, to derive a new delay-dependent sufficient condition on the existence of the H_∞ controller. The sufficient condition has been less conservative since we have successfully avoided: 1) overly bounding for some terms; 2) employing model transformation and bounding technique for some cross terms that are widely used in the existing literature; and 3) introducing slack variables. The effectiveness of the proposed results has been shown through two numerical examples.

REFERENCES

- [1] L. E. Ghaoui, F. Oustry, and M. AitRami, "A cone complementarity linearization algorithm for static output-feedback and related problems," *IEEE Trans. Autom. Control*, vol. 42, no. 8, pp. 1171–1176, Aug. 1997.
- [2] F. Gökas, "Distributed control of systems over communication networks," Ph.D. dissertation, Univ. Pennsylvania, Philadelphia, 2000.
- [3] Y. Halevi and A. Ray, "Integrated communication and control systems: Part I—analysis," *J. Dyn. Syst., Meas., Control*, vol. 110, no. 4, pp. 367–373, Dec. 1988.
- [4] Q.-L. Han, "On robust stability of neutral systems with time-varying discrete delay and norm-bounded uncertainty," *Automatica*, vol. 40, no. 6, pp. 1087–1092, Jun. 2004.
- [5] Q.-L. Han, "Robust stability for a class of linear systems with time-varying delay and nonlinear perturbations," *Comput. Math. Appl.*, vol. 47, no. 8/9, pp. 1201–1209, Apr./May 2004.
- [6] Q.-L. Han, "Absolute stability of time-delay systems with sector-bounded nonlinearity," *Automatica*, vol. 41, no. 12, pp. 2171–2176, Dec. 2005.
- [7] O. C. Imer, S. Yüksel, and T. Başar, "Optimal control of LTI systems over unreliable communication links," *Automatica*, vol. 42, no. 9, pp. 1429–1439, Sep. 2006.
- [8] D. Kim, Y. Lee, W. Kwon, and H. Park, "Maximum allowable delay bounds of networked control systems," *Control Eng. Practice*, vol. 11, no. 11, pp. 1301–1313, Nov. 2003.
- [9] F.-L. Lian, J. Moyne, and D. Tilbury, "Network design consideration for distributed control systems," *IEEE Trans. Control Syst. Technol.*, vol. 10, no. 2, pp. 297–307, Mar. 2002.
- [10] H. Lin, G. Zhai, and P. J. Antsaklis, "Robust stability and disturbance attenuation analysis for a class of networked control systems," in *Proc. 42nd IEEE Conf. Decis. Control (CDC 2003)*, Dec., pp. 1182–1187.
- [11] B. Lincoln and B. Bernhardsson, "Optimal control over networks with long random delays," in *Proc. Int. Symp. Math. Theory Netw. Syst. (MTNS)*, 2000.
- [12] Q. Ling and M. D. Lemmon, "Optimal dropout compensation in networked control systems," in *Proc. 42nd IEEE Conf. Decis. Control (CDC 2003)*, Dec., pp. 670–675.
- [13] X. Mao, N. Koroleva, and A. Rodkina, "Robust stability of uncertain stochastic differential delay equations," *Syst. Control Lett.*, vol. 35, no. 5, pp. 325–336, Dec. 1998.
- [14] Y. Moon, P. Park, and W. Kwon, "Delay-dependent robust stabilization of uncertain state-delayed systems," *Int. J. Control*, vol. 74, no. 14, pp. 1447–1455, Sep. 2001.
- [15] J. Nilsson, "Real-time control systems with delays," Ph.D. dissertation, Lund Inst. Technol., Lund, Sweden, 1998.
- [16] H. Park, Y. Kim, D. Kim, and W. Kwon, "A scheduling method for network based control systems," *IEEE Trans. Control Syst. Technol.*, vol. 10, no. 10, pp. 318–330, May 2002.
- [17] D. Peaucelle and F. Gouaisbaut, "Discussion on: 'Parameter-dependent Lyapunov function approach to stability analysis and design for uncertain systems with time-varying delay'," *Eur. J. Control*, vol. 11, no. 1, pp. 69–70, Jan. 2005.
- [18] P. Seiler, "Coordinated control of unmanned aerial vehicles," Ph.D. dissertation, Univ. California, Berkeley, 2001.
- [19] B. Sinopoli, L. Schenato, M. Franceschetti, K. Poolla, M. I. Jordan, and S. S. Sastry, "Kalman filtering with intermittent observations," *IEEE Trans. Autom. Control*, vol. 49, no. 9, pp. 1453–1464, Sep. 2004.
- [20] G. C. Walsh, H. Ye, and L. G. Bushnell, "Stability analysis of networked control systems," *IEEE Trans. Control Syst. Technol.*, vol. 10, no. 3, pp. 438–446, May 2002.
- [21] F. Yang, Z. Wang, Y. S. Hung, and M. Gani, " H_∞ control for networked systems with random communication delays," *IEEE Trans. Autom. Control*, vol. 51, no. 3, pp. 511–518, Mar. 2006.
- [22] T. Yang, "Networked control system: A brief survey," in *Inst. Electr. Eng. Proc. Control Theory Appl.*, Jul. 2006, vol. 153, no. 4, pp. 403–411.
- [23] D. Yue, Q.-L. Han, and C. Peng, "State feedback controller design of networked control systems," *IEEE Trans. Circuits Syst.—II: Exp. Briefs*, vol. 51, no. 11, pp. 640–644, Nov. 2004.
- [24] D. Yue, Q.-L. Han, and J. Lam, "Network-based robust H_∞ control of systems with uncertainty," *Automatica*, vol. 41, no. 6, pp. 999–1007, Jun. 2005.
- [25] W. Zhang, M. Branicky, and S. Phillips, "Stability of networked control systems," *IEEE Control Syst. Mag.*, vol. 21, no. 1, pp. 84–99, Feb. 2001.
- [26] M. Zhong, L. Jia, and J. Wang, "An LMI approach to H_∞ control of networked control systems," *Syst. Sci.*, vol. 29, no. 1, pp. 47–60, 2004.

Parametrization of the Regular Equivalences of the Canonical Controller

A. Agung Julius, Jan Willem Polderman, and Arjan van der Schaft

Abstract—We study control problems for linear systems in the behavioral framework. Our focus is a class of regular controllers that are equivalent to the canonical controller. The canonical controller is a particular controller that is guaranteed to solve the control problem whenever a solution exists. However, it has been shown that, in most cases, the canonical controller is not regular. The main result of the note is a parametrization of all regular controllers that are equivalent to the canonical controller. The parametrization is then used to solve two control problems. The first problem is related to designing a regular controller that uses as few control variables as possible. The second problem is to design a regular controller that satisfies a predefined input–output partitioning constraint. In both problems, based on the parametrization, we present algorithms for designing the controllers.

Index Terms—Behavior, canonical controller, input–output partition, regularity.

I. INTRODUCTION

In this note, we discuss control problems for linear differential systems in the behavioral approach. The behavior of the systems discussed in this note is the set of solutions of the linear differential equations that describe the systems [1]. In particular, we restrict our attention to the class of infinitely differentiable functions \mathcal{C}^∞ . Thus, whenever a differential equation is given, we assume its solution to be infinitely differentiable.

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Standard control problems in the behavioral approach to systems theory can be formulated as follows [2]–[4]. A plant to be controlled that has two kinds of variables, *to-be-controlled variables* and *control variables*, is given. Throughout this note, we denote the control variables by c and the to-be-controlled variables by w . The dimensions of c and w are denoted by c and w , respectively. A behavioral model of the plant system that captures the relevant relation between w and c is called the *full plant behavior*, and is denoted by $\mathcal{P}_{\text{full}}$. The full plant behavior can be compactly represented as the set of all signal pairs (w, c) that are strong solutions to an associated system of linear differential equations [1]

$$\mathcal{P}_{\text{full}} := \left\{ (w, c) \in \mathcal{C}^\infty(\mathbb{R}, \mathbb{R}^{w+c}) \mid R \left(\frac{d}{dt} \right) w + M \left(\frac{d}{dt} \right) c = 0 \right\} \quad (1)$$

where R and M are polynomial matrices of appropriate dimensions. We denote the class of polynomial matrices with indeterminate ξ , g rows, and q columns over the real field as $\mathbb{R}^{g \times q}[\xi]$. A representation of the behavior in the form of (1) is called a *kernel representation*, the reason being that the behavior is simply the kernel of a linear differential operator.

A *controller* is a device that is attached to (or an algorithm that acts on) the control variables and restricts their behavior. This restriction is imposed on the plant via the control variables, such that it (indirectly) affects the behavior of the to-be-controlled variables. A controller \mathcal{C} is thus a behavior containing all signals c allowed by the controller

$$\mathcal{C} := \left\{ c \in \mathcal{C}^\infty(\mathbb{R}, \mathbb{R}^c) \mid C \left(\frac{d}{dt} \right) c = 0 \right\}. \quad (2)$$

The resulting behavior is called the *controlled system*. The *controlled behavior* is then defined as

$$\mathcal{K} := \{ w \in \mathcal{C}^\infty(\mathbb{R}, \mathbb{R}^w) \mid \exists c \in \mathcal{C}^\infty(\mathbb{R}, \mathbb{R}^c) \text{ such that } (w, c) \in \mathcal{P}_{\text{full}} \text{ and } c \in \mathcal{C} \}. \quad (3)$$

The controlled behavior \mathcal{K} is obtained by eliminating the control variables c from the following kernel representation

$$\begin{bmatrix} R \left(\frac{d}{dt} \right) & M \left(\frac{d}{dt} \right) \\ 0 & C \left(\frac{d}{dt} \right) \end{bmatrix} \begin{bmatrix} w \\ c \end{bmatrix} = 0. \quad (4)$$

If we eliminate the control variables from the full behavior, we obtain the so-called *manifest behavior*, which is denoted by \mathcal{P} . Thus

$$\mathcal{P} := \{ w \in \mathcal{C}^\infty(\mathbb{R}, \mathbb{R}^w) \mid \exists c \in \mathcal{C}^\infty(\mathbb{R}, \mathbb{R}^c) \text{ such that } (w, c) \in \mathcal{P}_{\text{full}} \}. \quad (5)$$

As a part of the control problem, one is given a *specification*, which is expressed in terms of the to-be-controlled variables. The specification \mathcal{S} is given by the following kernel representation

$$\mathcal{S} := \left\{ w \in \mathcal{C}^\infty(\mathbb{R}, \mathbb{R}^w) \mid S \left(\frac{d}{dt} \right) w = 0 \right\}. \quad (6)$$

The objective of the control problem is to find a controller \mathcal{C} such that $\mathcal{K} = \mathcal{S}$. If such a controller exists, then the specification \mathcal{S} is said to be *implementable* and the controller \mathcal{C} is said to implement \mathcal{S} .

In [5] and [6], a particular controller design called the *canonical controller* was introduced. This design has the nice property that it implements the desired specification if and only if the specification is

implementable. However, an analysis on the regularity of the canonical controller reveals that it is *maximally irregular* [7]. Regularity is a desirable property for the interconnection [2], [3], which we will explain in Section II. We show that there exist regular controllers that are equivalent to the canonical controller, and we provide a parametrization of all such controllers. This parametrization is then used to solve the following two control problems.

- 1) The problem of *control with minimal interaction* [8]. This problem is about designing a regular controller that interacts with the plant with as few control variables as possible. The motivation behind this problem is as follows. Consider a situation where the plant and the controller are separated by a large physical distance. We need a communication link between the plant and the controller to establish the interconnection. It is therefore favorable to have as few control variables as possible, so that the amount of communication links/channels can be minimized.
- 2) The problem of *control with input–output partitioning constraint*. This problem is about designing a regular controller, in which some predetermined control variables remain free in the controller.

II. BACKGROUND MATERIAL

Kernel representations of a given behavior are not unique. Nevertheless, for any behavior \mathfrak{B} , there is a unique integer $p(\mathfrak{B})$, which is the minimum number of rows that a kernel representation of \mathfrak{B} can have. This number is also the row rank of any kernel representation of the behavior. A kernel representation with the minimum number of rows (i.e., equal to its row rank) is called a *minimal kernel representation*.

Suppose that a behavior \mathfrak{B} is given by

$$\mathfrak{B} := \left\{ w \mid R \left(\frac{d}{dt} \right) w = 0 \right\} \quad (7)$$

where R is full row rank and has $p(\mathfrak{B})$ rows. We can permute and partition the variables in w into w_1 and w_2 , such that (7) becomes

$$\mathfrak{B} := \left\{ (w_1, w_2) \mid R_1 \left(\frac{d}{dt} \right) w_1 + R_2 \left(\frac{d}{dt} \right) w_2 = 0 \right\} \quad (8)$$

where R_1 is a square full row rank polynomial matrix. Such a partition is called an *input–output partition*, where w_1 is the output and w_2 is the input to the system. Notice that the number of outputs of \mathfrak{B} is $p(\mathfrak{B})$.

Given a control problem, the implementability of a specification \mathcal{S} is a property that depends on the specification itself as well as the plant. The following result is proven in [9] and [10].

Lemma 1 (Willems' lemma): Given $\mathcal{P}_{\text{full}}$ as a kernel representation of (1). A specification \mathcal{S} is implementable if and only if $\mathcal{N} \subseteq \mathcal{S} \subseteq \mathcal{P}$, where \mathcal{N} is the *hidden behavior* defined by $\mathcal{N} := \{ w \in \mathcal{C}^\infty(\mathbb{R}, \mathbb{R}^w) \mid (w, 0) \in \mathcal{P}_{\text{full}} \}$.

Quite often, in addition to requiring that the controller implements the desired specification, we also require that the controller possesses a certain property with respect to the plant. A concept that has been quite extensively studied is the so-called *regularity property* [3], [11]–[13]. A controller

$$\mathcal{C} = \left\{ c \in \mathcal{C}^\infty(\mathbb{R}, \mathbb{R}^c) \mid C \left(\frac{d}{dt} \right) c = 0 \right\} \quad (9)$$

where C is full row rank, to be regular if

$$\text{rank} \begin{bmatrix} R & M \\ 0 & C \end{bmatrix} = \text{rank} [R \quad M] + \text{rank } C. \quad (10)$$

It can be proven that nonregular interconnections might affect the autonomous part of the plant or the controller [2], [14], which, in many cases would be undesirable or unrealistic.

If the specification S is such that there exists a regular controller C that implements it, then S is said to be *regularly implementable*. Necessary and sufficient conditions for regular implementability were derived in [3].

Theorem 2: Given the full plant behavior $\mathcal{P}_{\text{full}}$, a specification S is regularly implementable if and only if: 1) it is implementable, i.e., $\mathcal{N} \subseteq S \subseteq \mathcal{P}$ and 2) $S + \mathcal{P}^{\text{ctr}} = \mathcal{P}$. The symbol \mathcal{P}^{ctr} denotes the controllable part of the manifest behavior \mathcal{P} .

III. CANONICAL CONTROLLER AND ITS REGULAR EQUIVALENCES

In this section, we review the idea of the canonical controller and its properties [6]. Given a full plant behavior $\mathcal{P}_{\text{full}}$ and a specification S , the behavior of the canonical controller \mathcal{C}_{can} is defined as

$$\mathcal{C}_{\text{can}} := \{c \in \mathcal{C}^\infty(\mathbb{R}, \mathbb{R}^c) \mid \exists w \in \mathcal{C}^\infty(\mathbb{R}, \mathbb{R}^w) \text{ such that } (w, c) \in \mathcal{P}_{\text{full}} \text{ and } w \in S\}. \quad (11)$$

A kernel representation of the canonical controller can be obtained by eliminating w from the following kernel representation

$$\begin{bmatrix} R \left(\frac{d}{dt} \right) & M \left(\frac{d}{dt} \right) \\ S \left(\frac{d}{dt} \right) & 0 \end{bmatrix} \begin{bmatrix} w \\ c \end{bmatrix} = 0. \quad (12)$$

For the canonical controller, the following result holds.

Theorem 3: (cf. [6]) The canonical controller \mathcal{C}_{can} implements the specification S if and only if S is implementable.

We define the *control manifest behavior* of the plant as

$$\mathcal{P}_c := \{c \in \mathcal{C}^\infty(\mathbb{R}, \mathbb{R}^c) \mid \exists w \in \mathcal{C}^\infty(\mathbb{R}, \mathbb{R}^w) \text{ such that } (w, c) \in \mathcal{P}_{\text{full}}\}. \quad (13)$$

A kernel representation of \mathcal{P}_c can be obtained by eliminating w from the kernel representation of $\mathcal{P}_{\text{full}}$.

Despite the nice property given in the previous theorem, the canonical controller also has the property of being *maximally irregular*, in the following sense.

Theorem 4: (cf. [7]) Assume that the specification S is implementable. The canonical controller \mathcal{C}_{can} is regular if and only if every controller that implements S is regular.

In this note, we want to show that if the specification S is regularly implementable at all, then, although the canonical controller itself is maximally irregular, there exist regular controllers that are equivalent to it. By equivalent controllers, we mean controllers that allow the same set of c trajectories of the plant as the canonical controller does. The class of such controllers is defined as follows.

Definition 5: The class of regular controllers that are equivalent to the canonical controller is denoted by $\mathcal{C}_{\text{can}}^{\text{reg}}$, and is defined as

$$\mathcal{C}_{\text{can}}^{\text{reg}} := \{C \mid C \text{ is regular and } C \cap \mathcal{P}_c = \mathcal{C}_{\text{can}} \cap \mathcal{P}_c\}. \quad (14)$$

The following theorem provides necessary and sufficient conditions for the nonemptiness of the class $\mathcal{C}_{\text{can}}^{\text{reg}}$. This theorem is given without proof due to space limitation. The reader is referred to [8] and [14] for the proof, and to [15] and [16] for related results for nD behaviors.

Theorem 6: The class $\mathcal{C}_{\text{can}}^{\text{reg}}$ is nonempty if and only if the specification S is regularly implementable.

In fact, regular implementability of the specification S also implies that, for every regular controller that implements S , there exists a superset of that controller in $\mathcal{C}_{\text{can}}^{\text{reg}}$ that implements S . This is the content of the following theorem.

Theorem 7: [8], [14] Given a full plant behavior $\mathcal{P}_{\text{full}}$ and a regularly implementable specification S . If C is a regular controller that implements S , then there exists a regular controller $C' \in \mathcal{C}_{\text{can}}^{\text{reg}}$ that implements S and $C \subseteq C'$.

Given the importance of the set $\mathcal{C}_{\text{can}}^{\text{reg}}$ in this note, we present a parametrization of all controllers in $\mathcal{C}_{\text{can}}^{\text{reg}}$. Before we can obtain the parametrization, we need the following lemma.

Lemma 8: [8], [14] Let a plant \mathcal{P} be given as the kernel of a full row rank $R(d/dt)$ and a regular controller C be given as the kernel of a full row rank $C(d/dt)$. Denote the full interconnection by $\mathcal{K} := \mathcal{P} \cap \mathcal{C}$. Let $\mathcal{C}_{\mathcal{K}}$ denote the set of all controllers (not necessarily regular ones) that: 1) have at most as many outputs as C and 2) also implement \mathcal{K} when interconnected with \mathcal{P} . A controller $C' \in \mathcal{C}_{\mathcal{K}}$ if and only if its kernel representation can be written as $VR + C$ for some matrix V . Moreover, every controller in $C' \in \mathcal{C}_{\mathcal{K}}$ has the properties that: 1) C' is regular and 2) C' has exactly as many outputs as C . Notice that the number of outputs is $p(\mathcal{K}) - p(\mathcal{P})$.

If we pick any regular controller $C \in \mathcal{C}_{\text{can}}^{\text{reg}}$, Lemma 8 can be used to parametrize all other controllers in $\mathcal{C}_{\text{can}}^{\text{reg}}$ based on a kernel representation of C . This is one of the main results of this note, which is summarized in the following theorem.¹

Theorem 9: [14] Let the control manifest behavior of the plant \mathcal{P}_c be the kernel of $P_c(d/dt)$ and a controller $C \in \mathcal{C}_{\text{can}}^{\text{reg}}$ be the kernel of $C(d/dt)$. Assume that both P_c and C are full row rank. A controller C' is an element of $\mathcal{C}_{\text{can}}^{\text{reg}}$ if and only if it is the kernel of $V(d/dt)P_c(d/dt) + C(d/dt)$ for some polynomial matrix $V(\xi)$.

Proof: The full plant behavior can be represented by

$$\begin{bmatrix} \tilde{R} \left(\frac{d}{dt} \right) & \tilde{M} \left(\frac{d}{dt} \right) \\ 0 & P_c \left(\frac{d}{dt} \right) \end{bmatrix} \begin{bmatrix} w \\ c \end{bmatrix} = 0 \quad (15)$$

where \tilde{R} is full row rank. It follows that a controller C' represented as the kernel of $C'(d/dt)$ is regular if and only if

$$\text{rank} \begin{bmatrix} P_c \\ C' \end{bmatrix} = \text{rank } P_c + \text{rank } C'. \quad (16)$$

This is equivalent to saying that the interconnection of \mathcal{P}_c and C' is regular. Therefore, we can apply Lemma 8 (by replacing \mathcal{K} with \mathcal{C}_{can} and \mathcal{P} with \mathcal{P}_c) and obtain the parametrization of all elements in $\mathcal{C}_{\text{can}}^{\text{reg}}$.

IV. CONTROL WITH MINIMAL INTERACTION

Consider the following definition of irrelevant variables.

Definition 10: Let a behavior \mathfrak{B} be given by the kernel representation

$$R_1 \left(\frac{d}{dt} \right) w_1 + R_2 \left(\frac{d}{dt} \right) w_2 = 0. \quad (17)$$

The variables in w_1 are said to be *irrelevant* to \mathfrak{B} if \mathfrak{B} can be written as $\mathcal{C}^\infty(R, R^{w_1}) \times \mathfrak{B}_2$, where \mathfrak{B}_2 is the behavior of w_2 .

Notice that w_1 being irrelevant to \mathfrak{B} in (17) is equivalent with $R_1 = 0$. The number of irrelevant variables in a behavior \mathfrak{B} is thus the number of zero columns in a kernel representation of it. For any system

¹ We refer the reader to [17] for related results.

\mathfrak{B} , denote the number of its irrelevant variables by $i(\mathfrak{B})$. It can be proven that $i(\mathfrak{B})$ is independent of the choice of kernel representation of \mathfrak{B} . The problem of control with minimal interaction that we are addressing in this note can be formulated as follows.

Control with minimal interaction. Given are the full plant behavior $\mathcal{P}_{\text{full}}$ (1) and specification \mathcal{S} . We assume that the specification \mathcal{S} is regularly implementable. Construct a regular controller \mathcal{C} such that: 1) \mathcal{C} implements \mathcal{S} and 2) if \mathcal{C}' is a regular controller that implements \mathcal{S} , then $i(\mathcal{C}) \geq i(\mathcal{C}')$.

A controller that satisfies the aforementioned requirements is called a *controller with minimal interaction*. When some control variables are irrelevant to the controller, we can realize the controller without using these variables. A controller with minimal interaction is thus a controller that uses the fewest number of variables in its realization. Notice that such a controller is generally not unique.

We use the parametrization of $\mathfrak{C}_{\text{can}}^{\text{reg}}$ that we derived in the previous section to solve the problem of control with minimal interaction. First, consider the following lemma.

Lemma 11: Let \mathfrak{B} be a behavior, whose variables include the variable w_1 . If w_1 is irrelevant to \mathfrak{B} , then it is also irrelevant to any $\mathfrak{B}' \supseteq \mathfrak{B}$.

Lemma 11 and Theorem 7 tell us that it is sufficient to search for a controller with minimal interaction in $\mathfrak{C}_{\text{can}}^{\text{reg}}$, instead of in the set of all regular controllers. This is an advantage, since we can parametrize all the controllers in $\mathfrak{C}_{\text{can}}^{\text{reg}}$, as shown in Theorem 9. To solve the problem of control with minimal interaction, we need to find an element of $\mathfrak{C}_{\text{can}}^{\text{reg}}$ with the maximal number of zero columns. Generally, since there are finitely many columns, there is a maximal number of zero columns that can be attained. However, there is no guarantee that this number is attained by a unique controller. In fact, generally speaking, it is not.

The procedure to compute a regular controller that implements \mathcal{S} and has the maximal number of irrelevant variables can be summarized as follows.

- Step 1) Construct the canonical controller \mathcal{C}_{can} for the problem. Since \mathcal{S} is regularly implementable, we know that the canonical controller implements \mathcal{S} .
- Step 2) Construct a controller $\mathcal{C} \in \mathfrak{C}_{\text{can}}^{\text{reg}}$. Denote a kernel representation of \mathcal{C} and the control manifest behavior \mathcal{P}_c by $C(d/dt)$ and $P(d/dt)$, respectively.
- Step 3) The kernel representation of the controller with minimal interaction can be found by finding a matrix V such that $C + VP$ has the maximal number of zero columns.

The algebraic problem related to the third step has a combinatorial aspect in it, as we generally need to search for the answer by trying all possible subsets of the columns. This situation gives rise to a computational challenge, namely to design an algorithm that can handle this combinatorial problem efficiently. We refer the reader to [18] for an algorithm that solves the combinatorial problem. The following lemma establishes an upper bound for the number of irrelevant variables that can be attained in the controller with minimal interaction.

Lemma 12: A controller with minimal interaction can have at most $c - p(\mathcal{C})$ irrelevant variables. Here, c denotes the number of all control variables (the number of components of \mathbf{c}) and $p(\mathcal{C})$ denotes the number of output variables in \mathcal{C} , which is the same for all regular controllers that implement \mathcal{S} .

Proof: From the definition of regularity, we know that all regular controllers that implement \mathcal{S} have the same number of outputs, i.e., $p(\mathcal{C})$. This is the number of rows in a minimal kernel representation of the controller. It is easily seen that the number of columns is c . If a regular controller has more than $c - p(\mathcal{C})$ irrelevant variables, then the nonzero entries of any kernel representation of it form a tall matrix, and thus cannot be minimal. ■

V. CONTROL PROBLEM WITH INPUT–OUTPUT PARTITION CONSTRAINT

In some cases, it is physically necessary to require that in a controller, some of the plant control variables are free variables, for example, because these variables are sensor outputs. The control problem with an input–output partitioning constraint for linear systems is formally defined as follows.

Control with input–output partition constraint. Given a control problem, where the plant is

$$\mathcal{P} = \left\{ (w, c_1, c_2) \mid R \left(\frac{d}{dt} \right) w + P \left(\frac{d}{dt} \right) c_1 + Q \left(\frac{d}{dt} \right) c_2 = 0 \right\}. \quad (18)$$

The control variables are c_1 and c_2 , the to-be-controlled variable is w . The desired specification is given as

$$\mathcal{S} = \left\{ w \mid S \left(\frac{d}{dt} \right) w = 0 \right\}. \quad (19)$$

Find a regular controller \mathcal{C} described as

$$\mathcal{C} = \left\{ (c_1, c_2) \mid C_1 \left(\frac{d}{dt} \right) c_1 + C_2 \left(\frac{d}{dt} \right) c_2 = 0 \right\} \quad (20)$$

such that \mathcal{C} implements \mathcal{S} and the variables in \mathcal{C} can be input–output partitioned such that c_2 is free in \mathcal{C} , i.e., for any $c_2 \in \mathfrak{C}^\infty(\mathbb{R}, \mathbb{R}^{c_2})$, there exists a $c_1 \in \mathfrak{C}^\infty(\mathbb{R}, \mathbb{R}^{c_1})$ such that $(c_1, c_2) \in \mathcal{C}$.

To solve the problem, we assume that the specification \mathcal{S} is regularly implementable (otherwise the problem is clearly not solvable).

Notation 13: We denote the class of regular controllers that implements \mathcal{S} as $\mathfrak{C}_{\mathcal{S}}^{\text{reg}}$.

To find a solution to the problem, we need to use the following result.

Lemma 14: Given a system

$$\mathcal{C} = \left\{ (c_1, c_2) \mid C_1 \left(\frac{d}{dt} \right) c_1 + C_2 \left(\frac{d}{dt} \right) c_2 = 0 \right\}. \quad (21)$$

Without loss of generality, we assume that $[C_1 \ C_2]$ is full row rank. The variable c_2 is free in \mathcal{C} if and only if C_1 is full row rank.

Using Lemma 14, we can reformulate the control problem as follows.

Problem. Find a controller $\mathcal{C} \in \mathfrak{C}_{\mathcal{S}}^{\text{reg}}$ in the form of

$$\mathcal{C} = \left\{ (c_1, c_2) \mid C_1 \left(\frac{d}{dt} \right) c_1 + C_2 \left(\frac{d}{dt} \right) c_2 = 0 \right\}$$

where C_1 is full row rank.

We shall use the following lemma to show that we can restrict our attention to controllers in $\mathfrak{C}_{\text{can}}^{\text{reg}}$ in solving the problem.

Lemma 15: Let X be a subset of $\mathfrak{C}_{\mathcal{S}}^{\text{reg}}$ such that for any $\mathcal{C} \in \mathfrak{C}_{\mathcal{S}}^{\text{reg}}$, there exists a $\mathcal{C}' \in X$ such that $\mathcal{C} \subseteq \mathcal{C}'$. Then there exists a $\mathcal{C} \in \mathfrak{C}_{\mathcal{S}}^{\text{reg}}$ that solves the control problem with input–output partitioning constraint if and only if there exists a $\mathcal{C}' \in X$ that does so.

This lemma tells us that if we can construct a subset of $\mathfrak{C}_{\mathcal{S}}^{\text{reg}}$ with the property of X , we do not need to search for the candidate controller in the whole $\mathfrak{C}_{\mathcal{S}}^{\text{reg}}$. Rather, we can restrict our attention in X . Theorem 7 shows that $\mathfrak{C}_{\text{can}}^{\text{reg}}$ has the desired property. Thus, we shall try to construct the desired controller in $\mathfrak{C}_{\text{can}}^{\text{reg}}$, which we can parametrize according to Theorem 9.

A solution to the control problem can be found by executing the following steps.

- Step 1) Construct the canonical controller \mathcal{C}_{can} for the problem. Since \mathcal{S} is regularly implementable, we know that the canonical controller implements \mathcal{S} .

Step 2) Construct a controller $\mathcal{C} \in \mathfrak{C}_{\text{can}}^{\text{reg}}$. The proof of Theorem 6 contains information on how to construct \mathcal{C} from a regular controller. Denote the kernel representation of \mathcal{C} and the control manifest behavior \mathcal{P}_c , respectively, by

$$\mathcal{C} = \left\{ (c_1, c_2) \mid C_1 \left(\frac{d}{dt} \right) c_1 + C_2 \left(\frac{d}{dt} \right) c_2 = 0 \right\} \quad (22a)$$

$$\mathcal{P}_c = \left\{ (c_1, c_2) \mid P_1 \left(\frac{d}{dt} \right) c_1 + P_2 \left(\frac{d}{dt} \right) c_2 = 0 \right\}. \quad (22b)$$

Step 3) Following Theorem 9, any controller \mathcal{C}' in $\mathfrak{C}_{\text{can}}^{\text{reg}}$ can be represented by

$$\mathcal{C}' = \left\{ (c_1, c_2) \mid (C_1 + V P_1) \left(\frac{d}{dt} \right) c_1 + (C_2 + V P_2) \left(\frac{d}{dt} \right) c_2 = 0 \right\}. \quad (23)$$

The kernel representation of a controller in $\mathfrak{C}_{\text{can}}^{\text{reg}}$ that satisfies the input–output partitioning constraint can be found by finding a matrix V such that $C_1 + V P_1$ is full row rank.

A necessary and sufficient condition for the existence of such a matrix V is given in the following lemma.

Lemma 16: Given polynomial matrices $C \in \mathbb{R}^{c \times q}[\xi]$ and $P \in \mathbb{R}^{p \times q}[\xi]$. There exists a polynomial matrix $V \in \mathbb{R}^{c \times p}[\xi]$ such that $C + V P$ is full row rank if and only if

$$\text{rank} \begin{bmatrix} P \\ C \end{bmatrix} \geq c.$$

We refer the reader to [18] for a proof of this lemma.

To conclude, the following is the algorithm to solve the control problem with input–output partitioning constraint.

Algorithm 17: The following steps provide a solution to the problem if and only if it is solvable.

- 1) Verify if the specification \mathcal{S} is regularly achievable. If so, go to step 2, otherwise the problem is not solvable.
- 2) Construct the canonical controller for this problem, and denote it by \mathcal{C}_{can} .
- 3) Construct a regular controller $\mathcal{C} \in \mathfrak{C}_{\text{can}}^{\text{reg}}$. Theorem 6 guarantees that this can be done. The controller \mathcal{C} and the control manifest behavior \mathcal{P}_c can be represented in the form shown in (22).
- 4) Verify if $\text{rank} \begin{bmatrix} M_1 \\ P_1 \end{bmatrix} \geq p(\mathcal{C})$, where $p(\mathcal{C})$ denotes the number of output variables of \mathcal{C} . If this condition is satisfied, go to step 5, otherwise the problem is not solvable.
- 5) Compute a V such that $C_1 + V P_1$ is full row rank. The existence of such V is guaranteed by Lemma 16. A controller that solves the control problem is given by

$$\mathcal{C}' = \left\{ (c_1, c_2) \mid (C_1 + V P_1) \left(\frac{d}{dt} \right) c_1 + (C_2 + V P_2) \left(\frac{d}{dt} \right) c_2 = 0 \right\}. \quad (24)$$

VI. CONCLUDING REMARKS

The main result of the note is a parametrization of all regular controllers that are equivalent to the canonical controller $\mathfrak{C}_{\text{can}}^{\text{reg}}$. This class of controllers has the following two nice properties.

- 1) All its members are regular controllers.

- 2) It acts as an upperbound to other regular controllers. This means, any regular controller is a subset of an element of $\mathfrak{C}_{\text{can}}^{\text{reg}}$.

The special properties of the class $\mathfrak{C}_{\text{can}}^{\text{reg}}$ and its parametrization are used to solve two control problems in the behavioral framework. The first control problem is related to designing a regular controller that uses as few control variables as possible. The second problem is about designing a regular controller that satisfies a predefined input–output partitioning.

The use of the parametrization of $\mathfrak{C}_{\text{can}}^{\text{reg}}$ is not necessarily limited to the aforementioned problems. An interesting problem is, for example, to use the parametrization to construct a regular controller with a MacMillan degree as small as possible [2]. Such a result can potentially lead to the solution to the long standing problem of regular feedback implementability [19].

REFERENCES

- [1] J. W. Polderman and J. C. Willems, *Introduction to Mathematical Systems Theory: A Behavioral Approach*. New York: Springer, 1998.
- [2] J. C. Willems, "On interconnections, control and feedback," *IEEE Trans. Autom. Control*, vol. 42, no. 3, pp. 326–339, Mar. 1997.
- [3] M. N. Belur and H. L. Trentelman, "Stabilization, pole placement and regular implementability," *IEEE Trans. Autom. Control*, vol. 47, no. 5, pp. 735–744, May 2002.
- [4] M. N. Belur, "Control in a behavioral context," Ph.D. dissertation, Univ. Groningen, Groningen, The Netherlands, Jun. 2003.
- [5] A. J. van der Schaft and A. A. Julius, "Achievable behavior by composition," in *Proc. 41st IEEE Conf. Decision Control*, Las Vegas, 2002, pp. 7–12.
- [6] A. J. van der Schaft, "Achievable behavior of general systems," *Syst. Control Lett.*, vol. 49, pp. 141–149, 2003.
- [7] A. A. Julius, J. C. Willems, M. N. Belur, and H. L. Trentelman, "The canonical controllers and regular interconnection," *Syst. Control Lett.*, vol. 54, pp. 787–797, 2005.
- [8] A. A. Julius, J. W. Polderman, and A. J. van der Schaft, "Controller with minimal interaction," presented at the IFAC World Congr., Prague, Czech Republic, 2005.
- [9] J. C. Willems, "Behaviors, latent variables, and interconnections," *Syst. Control Inf. (Japan)*, vol. 43, pp. 453–464, 1999.
- [10] J. C. Willems and H. L. Trentelman, "Synthesis of dissipative systems using quadratic differential forms—Part I," *IEEE Trans. Autom. Control*, vol. 47, no. 1, pp. 53–69, Jan. 2002.
- [11] J. W. Polderman, "Sequential continuous time adaptive control: A behavioral approach," in *Proc. 39th IEEE Conf. Decision Control*, Sydney, 2000, pp. 2484–2487.
- [12] A. A. Julius and A. J. van der Schaft, "Compatibility of behavior interconnections," presented at the Eur. Control Conf., Cambridge, U.K., Sep. 2003.
- [13] J. C. Willems, M. N. Belur, A. A. Julius, and H. L. Trentelman, "The canonical controller and its regularity," in *Proc. IEEE Conf. Decision Control*, Hawaii, Dec. 2003, pp. 1639–1644.
- [14] A. A. Julius, "On interconnection and equivalence of continuous and discrete systems: A behavioral perspective," Ph.D. dissertation, Univ. Twente, Enschede, The Netherlands, Feb. 2005.
- [15] P. Rocha, "Canonical controllers and regular implementation of nD behaviors," presented at the 16th IFAC World Congr., Prague, Czech Republic, 2005.
- [16] H. L. Trentelman and D. N. Avelli, "On the regular implementability of nd systems," *Syst. Control Lett.*, vol. 56, no. 4, pp. 265–271, 2007.
- [17] C. Praagman, H. L. Trentelman, and R. Z. Yoe, "On the parametrization of all regularly implementing and stabilizing controllers," *SIAM J. Control Optim.*, vol. 45, no. 6, pp. 2035–2053, 2007.
- [18] A. A. Julius, J. W. Polderman, and A. J. van der Schaft, "Parametrization of the regular equivalences of the canonical controller and its applications," arXiv article nr. 0708.1309, Aug. 2007.
- [19] H. L. Trentelman, "Regular feedback implementability for linear differential behaviors," in *Unsolved Problems in Mathematical Systems and Control Theory*. Princeton, NJ: Princeton Univ. Press, 2004, pp. 44–48.